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1/f Noise in Carbon Nanotube Devices—On the Impact of Contacts and Device Geometry

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***Abstract*—We report on the 1/f noise in various ballistic carbon nanotube devices. A common means to characterize the quality of a transistor in terms of noise is to evaluate the ratio of the noise amplitude A and the sample resistance R. By contacting semiconducting tubes with different metal electrodes we are able to show that a small A/R value by itself is no indication of a suitable metal/tube combination for logic applications. We discuss how current in a nanotube transistor is determined by the injection of carriers at the electrode/nanotube interface, while at the same time excess noise is related to the number of carriers inside the nanotube channel. In addition, we demonstrate a substantial reduction in noise amplitude for a tube transistor with multiple carbon nanotubes in parallel.**

***Index Terms*—Carbon nanotube, field-effect transistor, 1/f noise.**

I. Introduction

SINCE nanomaterials have been used for transport studies it has been frequently observed that their electrical characteristics showed substantial low-frequency current fluctuations. Already in 2000 Collins *et al.* [1] classified those fluctuations in the case of carbon nanotubes (CNs) as 1/f-type. Later works confirmed this finding [2]–[5]. Interestingly, the same nanotubes were found to behave as ballistic conductors with mean free path of several hundred nanometers at room temperature a few years later [6], [7]. This is peculiar since in the past, only systems that exhibit diffusive transport properties have been associated with the aforementioned 1/f-type noise feature and it has been understood that scattering and noise are in general correlated [8]. Since nanotubes are considered to be one of the most promising contestants for future high-performance logic applications, it is imperative to gain a thorough understanding of this unexpected noise in CN devices and evaluate its implications for nanostructure based circuits.

In a previous work [3] we had found that the so-called excess noise in carbon nanotubes is not higher than in other materials, e.g., silicon, and is related to the small number of carriers inside the tube. Here we present a study that evaluates the 1/f noise in a ballistic, 1-D system, i.e., a semiconducting carbon nanotube, as a function of metal contact material and sample geometry in a field-effect transistor (FET) layout. We offer experimental evidence supporting our previous interpretation and present a more complete picture of the connection between electrical characteristics and noise in ballistic CNFETs. Moreover, we discuss an experimental implementation of a CNFET with substantially reduced noise characteristics and argue that low-noise circuits based on nanotubes will most likely have to employ devices with multiple gated nanotube segments in parallel.

Experiments are performed with CNFETs using one pair of source/drain contacts (type A) and up to 30 nanotube channels in parallel (type B). We show that the observed current and noise levels can be consistently explained within an extended Schottky barrier model for a ballistic, 1-D conductor in a nonequilibrium Green's function approach.

II. Device Fabrication

Nanotube transistors were fabricated from laser ablation [9] and arc-discharge tubes [10] (type A) and tubes grown by chemical vapor deposition (CVD) [11] (type B). Source/drain contacts consist of either aluminum, titanium or palladium. The distance between the source and drain electrode is around $L = 600$ nm for transistors of type A. For CNFETs made from 10 to 30 μm long CVD nanotubes the contact separation is around $L = 200$ nm. A gate controls the electrostatics inside the nanotube channel in the case of the laser ablation and arc-discharge tubes through a backside $t_{\rm ox} = 10$ nm silicon dioxide layer [see inset of Fig. 1(a)]. For the CVD grown tubes a similar gate control is obtained through a $t_{\rm ox} = 15$ nm thick alumina film fabricated by atomic layer deposition (ALD) on top of the nanotube prior to the metal gate formation.

The use of thin gate dielectric films is crucial for a reliable noise measurement. While applying a fixed gate voltage in the case of thick dielectric films usually results in a drift of the device current due to charging [12], the same can be prevented by using a thin gate oxide layer. Device characterization takes place under a small dc voltage ($\leq$ 100 mV) applied between the source and the drain electrode ($V_{\rm ds}$) at various gate voltages ($V_{\rm gs}$). The current I_d through the device is monitored by an HP parameter analyzer and the current noise spectral density S_I, i.e., the current power fluctuation (ΔI^2) per Hz is taken for a fixed set of $V_{\rm ds}$ and $V_{\rm gs}$ through a spectrum analyzer subsequently. The 1/f noise amplitude A is obtained using $A = S_I \cdot f/I^2$. Both I_d and S_I are measured at room-temperature.

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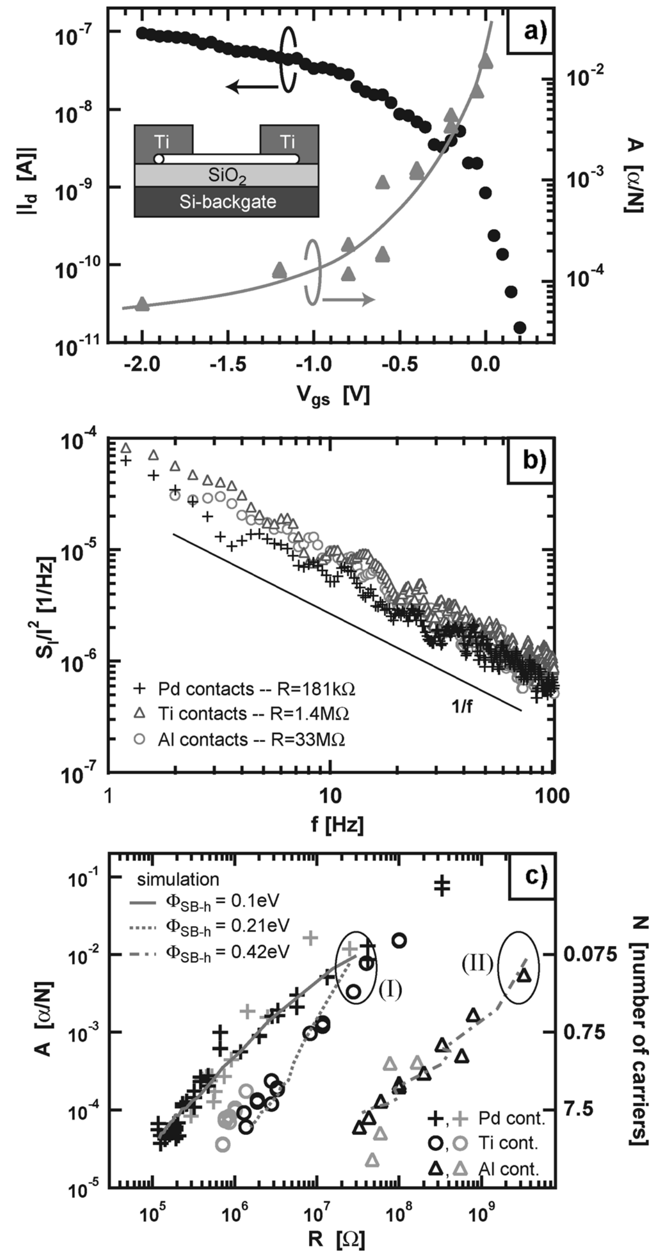

Fig. 1. (a) Device current I_d and noise amplitude A at $V_{\rm ds} = -0.1$ V as a function of gate voltage for a Ti-contacted sample. The gray line is a guide to the eyes. (b) Normalized current noise power spectral density as a function of frequency in the devices on-state for the three different contact metals used. (c) Noise amplitude A as a function of sample resistance for CNFETs of type A with three different contact metals. Black and gray symbols refer to different transistors respectively. The lines show the results of simulations using the extended Schottky barrier model.

III. Experimental Noise Characteristics, Simulations, and Interpretation

Fig. 1(a) shows a typical I_d versus $V_{\rm gs}$ measurement and the corresponding A versus $V_{\rm gs}$ data set for a Ti-contacted sample of type A.[1] While I_d decreases with increasing (more positive) $V_{\rm gs}$ as expected for a hole transport dominated FET, A on the other hand increases.

The same general trend is observed for all samples under consideration independent of contact type. In fact, the experimental finding is that different metal electrodes leave the noise amplitude A at a given overdrive $V_{\rm gs}-V_{\rm th}$ almost unaffected as shown in Fig. 1(b) while having at the same time a substantial impact on the current through the device as will be discussed below. Since the threshold voltage in our devices changes with the contact metal type [13] a more universal picture is obtained when A is plotted as a function of the sample resistance R. Note that the A/R metric has been proven to be useful for the characterization of 1/f noise in carbon nanotube devices before [2]. Different from these studies that were based on 2-D networks, R in our case is entirely determined by the transmission probability in the contact region due to the prevailing ballistic transport conditions [14], [15].

Plotting A versus R also ensures that the actual value of $V_{\rm ds}$ has no impact on the following discussion as long as the device current is measured in the linear $I_d - V_{\rm ds}$ range. Most importantly, this plot allows to compare electrical characteristics of devices exhibiting a nonideal gate voltage response, i.e., devices with a switching characteristic that is impacted by the existence of other charges in the vicinity of the nanotube.

Fig. 1(c) displays the dependence of noise amplitude A on R for the three metal contacts under consideration. The symbols indicate the experimental data with black and gray symbols referring to different CNFETs. Note that the noise amplitude spans a very similar A-range for the different contact types. At the same time we find substantially different values for $R_{\rm min}$, the minimum observed sample resistance.[2] For Pd-contacted nanotubes of type A, the resistance can be as small as 100 kΩ, while $R_{\rm min}$ is one and two orders of magnitude larger for the Ti- and Al-contacted devices, respectively. The curves for FETs with titanium and aluminum electrodes occur right-shifted nearly parallel to the R axis with respect to the Pd-sample. This particular behavior is specific for an injection controlled device. It is evidence for the independent control of current and noise in a semiconductor and implies that the A over R ratio alone is an inadequate means to characterize CNFETs. Indeed, devices exhibiting a smaller A over R ratio for a given resistance (e.g., Al-contacted samples versus Pd-contacted samples) are a less desirable choice when considering the device performance since small R-values are unachievable with certain source/drain electrodes.

To understand the current and noise response of the nanotube devices under investigation, it is critical to take a closer look at the impact of the gate on the electrostatic conditions inside the tube channel. Fig. 2 illustrates the band bending situation of the semiconducting carbon nanotube for three different contact Schottky barriers. The graph is a result of a self-consistent simulation we have performed using the nonequilibrium Green's function (NEGF) formalism [16]. The simulation considers a device that consists of a nanotube in contact with two metallic electrodes—the source and the drain—that act as electron/hole reservoirs. The charge in and current through the transistor are calculated self-consistently using the NEGF formalism together

[1]It is always ensured that we are indeed measuring the 1/f-type excess noise by monitoring both the frequency dependence as shown in Fig. 1(b) as well as the current dependence of S_I.

[2]Note that the device on-state is associated with the lowest observed R-values and no significant change of R is attainable once the gate voltage is sufficiently negative.

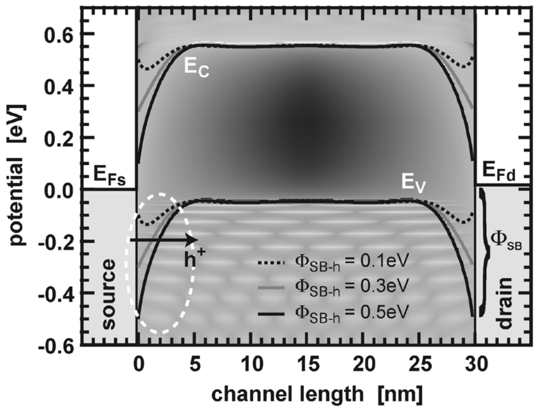

Fig. 2. Simulated band bending situation for a long-channel SB-CNFET for three different Schottky barrier heights $\Phi_{\rm SB-h}$ at the metal electrode/nanotube interface for $V_{\rm gs} = -1$ V and $V_{\rm ds} = -10$ mV.

with a modified 1-D Poisson equation according to Young [17] that accounts for the impact of gate oxide thickness $t_{\rm ox}$ and tube diameter $t_{\rm ch}$ on the electrostatics conditions inside the nanotube channel. A quadratic dispersion relation is assumed in the conduction and valence band and the complex band structure in the semiconducting nanotube gap is taken into account by an energy dependent effective mass [18]. Ballistic transport conditions are assumed as appropriate for our tube devices under small drain voltages. Despite the fact that this approach simplifies the actual situation, e.g., by assuming that the metal contacts behave as ideal conductors with a quadratic dispersion and free electron mass, quantitative agreement between experiment and simulation has been demonstrated over the course of the past years [13], [19].

Fig. 2 is the result of a simulation for a long-channel device with the electrostatics inside the channel being entirely controlled by the gate as apparent from the flat band region in the middle part of the nanotube. Note that as long as the source/drain separation L in the experiment remains smaller than the characteristic mean free scattering length at room-temperature in the nanotube, the experimental conditions are well described by our calculation even though much smaller actual L-values are simulated. For a fixed gate voltage (independent of the actual $V_{\rm gs}$ value) we observe that the valence band away from the contact region is at the same position relative to the source/drain Fermi level for all three contact Schottky barrier heights $\Phi_{\rm SB-h}$ under consideration. While this is an expected behavior for a charge-controlled device,[3] it is by no means a trivial statement for an injection-controlled transistor such as the CNFET. As has been pointed out before [20], the quantum capacitance C_q depends in general on the carrier injection conditions and thus also on $\Phi_{\rm SB-h}$ in an SB-CNFET. Only for the small drain voltages considered here and for not too thick gate oxides, the behavior displayed in Fig. 2 is observable.

The above discussion implies that indeed the number of carriers in the valence band is the same for $\Phi_{\rm SB-h} = 0.1$, 0.3, and 0.5 eV—except for the region close to the contacts. At the same time however, the current through the device is still determined by the transmission probability $T(E)$ for carriers (here holes) from the source contact into the nanotube channel as indicated by the white circled area in Fig. 2. The larger $\Phi_{\rm SB-h}$ the smaller the device current. Making the gate voltage more positive moves the bands downward. The number of holes inside the valence band decreases and at the same time $T(E)$ decreases since the Schottky barrier width increases. In summary, the simulation predicts the following: 1) The sample resistance R increases with increasing $\Phi_{\rm SB-h}$ while the number N of holes inside the nanotube remains the same; 2) R also increases with increasing positive gate voltage while N decreases—N however remains independent of Schottky barrier height for any given gate voltage. If we assume that N is inversely proportional to the noise amplitude, as we will argue in the following, the dependence of A on R displayed in Fig. 1(c) follows.

Already in 1969 Hooge [21] observed that for homogenous bulk-type materials the 1/f noise amplitude A scales inversely proportional to the total number N of free carriers that are involved in current transport. An empirical parameter—the Hooge's parameter $\alpha_H \sim 2 \cdot 10^{-3}$ relates A and N $(A = \alpha_H/N)$. While it was found later that α_H is by no means a universal constant but strongly depends on the material properties and the details of the sample [22], the general trend of A on N has been confirmed for numerous diffusive conductors and semiconductors.

Here we apply the same picture to the case of a ballistic, scattering-free system following our previous arguments [3] but with the extension that current and noise are independently impacted by the Schottky barriers. We argue that the number of free carriers (in this case holes) in the nanotube is a measure of the observed 1/f noise amplitude in carbon nanotubes.[4] First, we use the simulation approach described above to determine the current through a CNFET as a function of gate voltage for the three metal contacts in use. As we have shown in a previous publication [13], CNFET characteristics can be quantitatively reproduced for different contact metals if the nanotube diameter and Schottky barrier height at the metal nanotube interface are known. In order to realize the experimentally observed current variation as a function of $\Phi_{\rm SB-h}$ it had to be assumed that injection occurs from the segment of the nanotube directly underneath the metal contacts—rather than the metal itself—with a density of states that is modified by the proximity of the metal electrode in this region. To describe the coupling strength between the metal and the underlying nanotube, the self-energy that accounts for the contacts within the NEGF [16] is multiplied by a constant factor γ smaller than unity. In the following we will refer to this description as the "extended Schottky barrier model."

Consistent with the observations by Chen *et al.* [13], we extract the highest Schottky barriers of around 420 meV for Al-contacted samples and the lowest $\Phi_{\rm SB-h}$ values in the range

[3]A charge-controlled device is an FET whose current is either determined independent of contact transmission probability by scattering inside the gated channel region or, in case of a ballistic FET, a device with a transmission of unity at the contact-channel interface.

[4]Note that at this point in time the source of the 1/f noise in nanotubes is not known. While trapping and detrapping of carriers in the oxide underneath the nanotube is a plausible cause for the observed excess noise, our studies do not yet allow us to conclusively identify the noise origin.

of 100 meV for Pd-contacted devices.[5] Note, that the exact barrier height is a function of both, the contact metal and the nanotube diameter. Only if tubes of similar diameter are used for the same metal contact type, as in the present case [see black and gray symbols in Fig. 1(c)], a similar A versus R dependence is obtained. After having determined the device resistance as a function of gate voltage V_{gs} in this way, the number of free holes N in the system is extracted from the same simulation—again as a function of V_{gs}. N is obtained by summation of all occupied states in the valence band at room-temperature over the entire channel length. Since we are considering a system with open boundary conditions, i.e., with contacts attached to the semiconducting nanotube under finite drain voltage conditions, N does not have to be an integer number and can in fact even be smaller than one.

Fig. 1(c) summarizes the result of our simulations from the extended model with different Schottky barrier heights accounting for the three different contact metals used in the experiment for a constant $\alpha_H = 7.5 \cdot 10^{-4}$, consistent with the α_H value found before [3]. The quantitative agreement is apparent. Not only do our simulations reproduce the generic trends but they also capture a number of details that were not apparent from the qualitative arguments made above. For example, both experiment and simulation indicate that the two data sets for Ti- and Pd-contacted samples exhibit very similar A-R-values for the device off-state. At around 20 MΩ both types of FETs show similar A-values of approximately $A \approx 10^{-2}$ [see area marked (I) in Fig. 1(c)]. For Schottky barrier heights of $\Phi_{\mathrm{SB-h}} = 100$ and 210 meV, the off-state resistance of the CNFET becomes dominated by the potential barrier within the nanotube channel rather than by the contact Schottky barriers. This is the case for sufficiently high positive gate voltages when the barrier posed by the middle part of the channel becomes higher than $\Phi_{\mathrm{SB-h}}$. In this case the same resistance is reached for the Pd- and Ti-contacted samples for the same gate voltage. For large enough Schottky barriers as in the case of Al-contacted devices, however, the injection is always limited by the Schottky barriers. Accordingly, experiment and simulation show R-values for the Al-electrode FETs that are larger than for the Pd- and Ti-CNFETs for both the transistor on- and off-state (see area marked (II) in Fig. 1(c)).

IV. Reducing the Noise Figure in NanoCircuits

Our observations from above clearly indicate that merely evaluating pairs of R-A values is insufficient to identify the ideal device layout or sample treatment. Instead, the necessity of high on-currents for high-performance transistors makes using the best contact material—the one with the lowest Schottky barrier—for source/drain formation the foremost task. The only two possible approaches to obtain improved noise characteristics for a fixed type of contact are thus to reduce α_H and/or to increase the total number of carriers involved in current transport. A way of accomplishing the latter and to test this hypothesis is to create a CNFET with multiple gated channels in parallel. CNFETs of type B fall into this category.

[5]Gate oxide thickness, effective mass etc. were chosen to reflect the experimental conditions. $\gamma = 0.03$ was used in all simulations for samples of type A

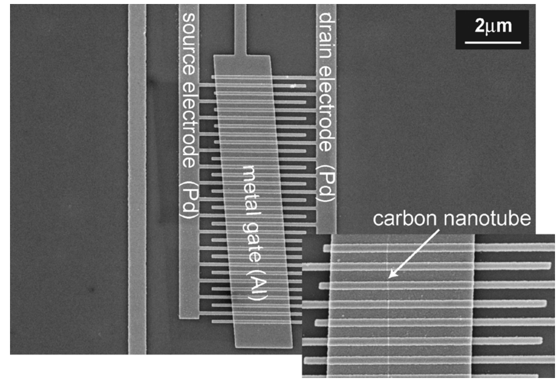

Fig. 3. SEM of a top-gated CNFET of type B. An individual CVD grown nanotube is contacted by multiple palladium electrodes resulting in 30 nanotube segments in parallel involved in current transport.

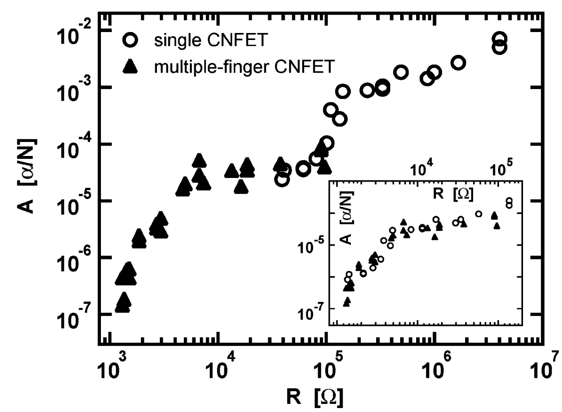

Fig. 4. Noise amplitude versus sample resistance for a device with 30 tube segments in parallel (black triangles) and for an individual tube (open circles) for comparison. The inset shows the same data set if R and A for the individual tube sample are both divided by 30.

With multiple nanotube segments in parallel, we expect that such a transistor shows: 1) a decrease of sample resistance by a factor X proportional to the number of parallel tubes due to the X-times larger current that is carried through the device and 2) a reduction in noise amplitude by the same factor X due to the X-times larger number of charges associated with the observed current fluctuations.

Fig. 3 shows an SEM image of a typical CNFET (type B) with multiple source/drain contacts and an Al-gate controlling the electrostatics in all nanotube segments simultaneously. A part of the same CVD grown nanotube is also used to build a nanotube transistor with just one source and drain contact (not shown). The same contact geometry and gate configuration is employed for this individual CNFET. Fig. 4 shows the dependence of noise amplitude A versus sample resistance R for those two types of CNFETs. While the noise amplitude and resistance of the individual CNFET are similar to the case of the Pd-contacted samples of type A discussed in the context of Fig. 1(c),[6] much smaller R and A values are observed for the multiple-finger device as expected. Moreover, as shown in the inset of Fig. 4, dividing the resistance and noise amplitude of the single CNFET by $X = 30$, the number of parallel tube segments

[6]We find that the pronounced knee structure in case of CVD grown tubes is a common feature that can be simulated assuming a smaller coupling constant γ than employed for the analysis of type A CNFETs.

involved in current transport for the multiple-finger device, results in an excellent agreement between the two data sets.

V. Summary and Conclusion

In summary, we have experimentally studied the impact of the source/drain contact material on the noise characteristics of CNFETs. Our findings are consistent with our previously proposed model in which the number of carriers inside the channel determines the noise amplitude in nanodevices. While at a first glance certain devices—as Al-contacted CNFETs—seem to exhibit a better A over R ratio, we have shown that this metric alone is insufficient to identify the optimum device geometry of nano-FETs. We have also demonstrated how noise characteristics can be substantially improved by means of a parallel-channel approach. Our findings imply, that without substantially reducing the value of the Hooge's parameter, a nanocircuit may always require the use of multiple nano-FET channels in parallel not only to reduce the absolute sample resistance but more importantly to control the intrinsic device noise level.

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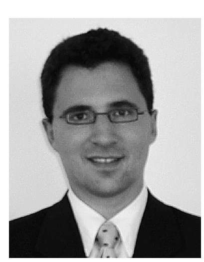

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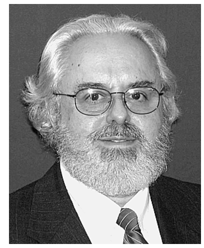

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After postdoctoral work at UCLA and AT&T Bell Laboratories, he joined the Research Division of IBM in 1978. He is an IBM Fellow and manager of Nanometer Scale Science and Technology at the IBM T.J. Watson Research Center, Yorktown Heights, New York. Over the years, his research has involved a wide variety of subjects ranging from laser studies of fast phenomena, surface physics and chemistry, scanning tunneling microscopy, and atom manipulation. He has published over 300 scientific papers. He is coeditor of the Springer-Verlag book series on Nanoscience and is currently serving on the Advisory Editorial Boards of *Nano Letters*, *Nanotechnology*, *International Journal of Nanoscience*, *Journal of Nanoengineering and Nanosystems*, *Journal of Computational and Theoretical Nanoscience*, *Surface Review and Letters*, and the *Journal of Electron Spectroscopy*. His current research is focused on experimental and theoretical studies of the electrical properties and transport mechanisms of carbon nanotubes, molecules and other nanostructures. The work includes the design, fabrication and study of model carbon nanotube and molecular electronic devices and circuits.

Dr. Avouris has been elected Fellow of the American Academy of Arts and Sciences, the American Physical Society, the Institute of Physics of the U.K., the IBM Academy of Technology, the American Association for the Advancement of Science, American Vacuum Society, and the New York Academy of Sciences. He is also member of the ACS and MRS. He received the Irving Langmuir Prize of the American Physical Society, the Medard W. Welch Award of the American Vacuum Society, the Feynman Prize for Molecular Nanotechnology, the ACSIN Nanoscience Prize, the Raper Award of IEEE, the Distinguished Alumnus Award from Michigan State University, and a number of IBM Corporation "Outstanding Technical Achievement" awards.